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AN EXPERIMENTAL STUDY OF HEAT TRANSFER IN MULTILAYER INSULATION SYSTEMS FROM ROOM TEMPERATURE TO 77 K*

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AN EXPERIMENTAL STUDY OF HEAT TRANSFER IN MULTILAYER INSULATION SYSTEMS FROM ROOM TEMPERATURE TO 77 K

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ABSTRACT

The total heat transfer from ~300 to 77 K was experimentally studied for a series of different arrangements of multilayer insulation (MLI) on black painted and aluminum taped copper surfaces. The heat flux as a function of the number of MLI layers and of the overall vacuum level was measured. The flux to a painted surface was 24.7 W/m^2 with no MLI and 0.64 W/m^2 with 30 layers, both at a vacuum of 1.5×10^{-5} torr. The values to a taped surface were 4.8 W/m^2 and 0.52 W/m^2. The use of aluminum tape permits one to use approximately one-half as many layers for the same heat flux. The heat flux was measured for six insulation systems from 1.5×10^{-5} torr to $\sim 1 \times 10^{-3}$ torr. The temperature distribution through the MLI was measured as a function of vacuum level. It was deduced that the apparent thermal conductivity increases with the distance from the cold surface. The effect of cracks in an MLI system was studied by cutting 6-mm wide cracks through a 90-layer blanket. The heat load increased by more than three times the value calculated from the exposed area only.

INTRODUCTION

The thermal performance of evacuated multilayer insulation (MLI) systems for use on liquid oxygen, nitrogen and hydrogen temperature surfaces was extensively studied in the 1960's. The superior performance of MLI systems, such as double-aluminized Mylar with a spacer and crinkled single-aluminized Mylar, compared to evacuated powder lead to its widespread adoption by industry for transport and storage tanks. Large superconducting magnet systems are usually radiation shielded by surfaces at 50 to 80 K which are multilayer insulated. The evacuation of the relatively small diameter (ϕ = 30 cm), long (several hundred meters) vacuum space on superconducting accelerator magnet sections can be very time consuming if the radiation shield has a typical 50 layers of MLI. The vacuum pumping characteristics may be improved by reducing the number of MLI layers. However the thermal performance of MLI must be understood

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in order to optimize the MLI-vacuum system. The heat transfer through multishields in high ($<10^{-3}$ torr) vacuum is by radiation, residual gas and solid conduction[1]:

$$Q = \frac{\sigma\, A\, (T_h^4 - T_c^4)\, E_o\, E_s}{(N-1)E_o + 2E_s} + \alpha\, C\, A\, P\, (T_h^{0.5} - T_c^{0.5}) + \frac{k\, \bar{A}\, (T_h - T_c)}{N\delta} .$$

A number of the parameters in this equation must in practice be experimentally determined. An experimental program was recently initiated to investigate heat transfer from ~300 to 77 K and to determine whether the use of aluminum tape is advantageous for the radiation shields of accelerator magnets arranged in extended, linear arrays. The program included measurements of (1) the heat flux as a function of the number of MLI layers and of the vacuum level, (2) the temperature distribution in the multilayer blanket as a function of vacuum level, and (3) the effect of a gap or crack in the MLI on the heat flux and temperature distribution. It was a continuation of a previous study[2] of heat transfer from 77 to 4.2 K.

EXPERIMENTAL APPARATUS

The apparatus used previously was modified to study heat transfer to a 77-K surface, Fig. 1. The surface area of the inner copper plate was 2.26 m^2. The outer copper box was maintained near room temperature by a series/parallel circuit of electrical resistors. The nitrogen boil-off vessel was shielded from ambient by a liquid nitrogen guard vessel and copper shields. To normalize the experimental conditions and simulate a badly oxidized surface, a black painted inner plate was used for some of the data runs. For other runs the inner plate was mechanically polished by hand or taped with 3M, #425 aluminum tape. Crinkled single-aluminized

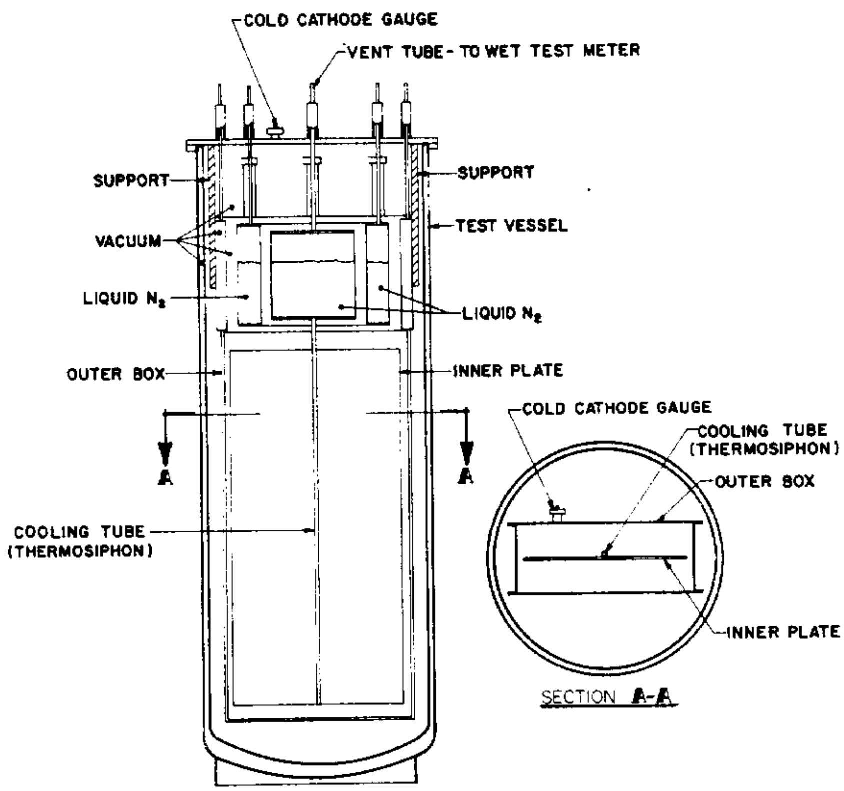

Fig. 1. Test apparatus.

Mylar multilayers (NRC-2* with aluminum thickness of 300 angstroms) were applied to the inner plate by hanging individual layers vertically and wrapping around the edges. The layer density was 11±2 cm^{-1}.

The inner plate was instrumented with copper-Constantan thermocouples and thermocouples were also inserted between selected layers of MLI. The thermocouples were read out by a scanner and digital indicator. The outer box was also instrumented with Cu-Constantan thermocouples, one of which was the sensor for a temperature controller.

The nitrogen gas boil off was measured with the same wet test meter as before, accurate to 0.2%. The correction factor required to relate the nitrogen boil off data to the evaporation rate (1.0058) was ignored for these measurements.

The insulating vacuum space was pumped with a cold-trapped diffusion pump. To measure the overall vacuum a cold cathode vacuum gauge was mounted on the lid and another on the box as shown in Fig. 1. Although cross calibrated the gauges did not always read the same. In the results presented here the vacuum measured by the gauge on the box is used. A block and bleed circuit was installed on the vacuum system to permit a known amount of helium gas to be added to the vacuum space[3] to simulate a leak in a liquid nitrogen shielded superconducting magnet or helium transfer line. With the pump valved off the vacuum level could be increased in steps of 1 x 10^{-5} torr.

A preliminary run of the apparatus was made without the inner plate and a background heat load of 0.49 W.

MEASUREMENTS AND RESULTS

General observations

The eight data runs given in Table 1 were made. Each run took 8 to 12 days, depending on whether data was taken as a function of vacuum level. During the first run the temperature of the inner plate was observed to be independent of position within the sensitivity of the thermocouple indicator, ± 0.25 K. The temperature of the box was 277.2 K (4°C) and was likewise independent of position and time to within ± 0.25 K. The temperature uniformity of the inner plate for the run with the highest heat load (#2) was ± 2 K. The box was maintained at 277 K for the heat flux measurements and at 288 K for the temperature distributions.

Measured heat flux with good vacuum

Figure 2 shows the heat flux deduced from the boil off data of the

Table 1. Experimental Program

Run Number	Surface of inner plate	Surface of box
1	polished copper	polished copper
2	copper with black paint	polished copper
3	same as #2, with 30 layers	polished copper
4	same as #2, with 60 layers	polished copper
5	same as #2, with 90 layers	polished copper
6	same as #2, 90 layers with cracks	polished copper
7	copper with aluminum tape	polished copper
8	same as #7, with 30 layers	polished copper

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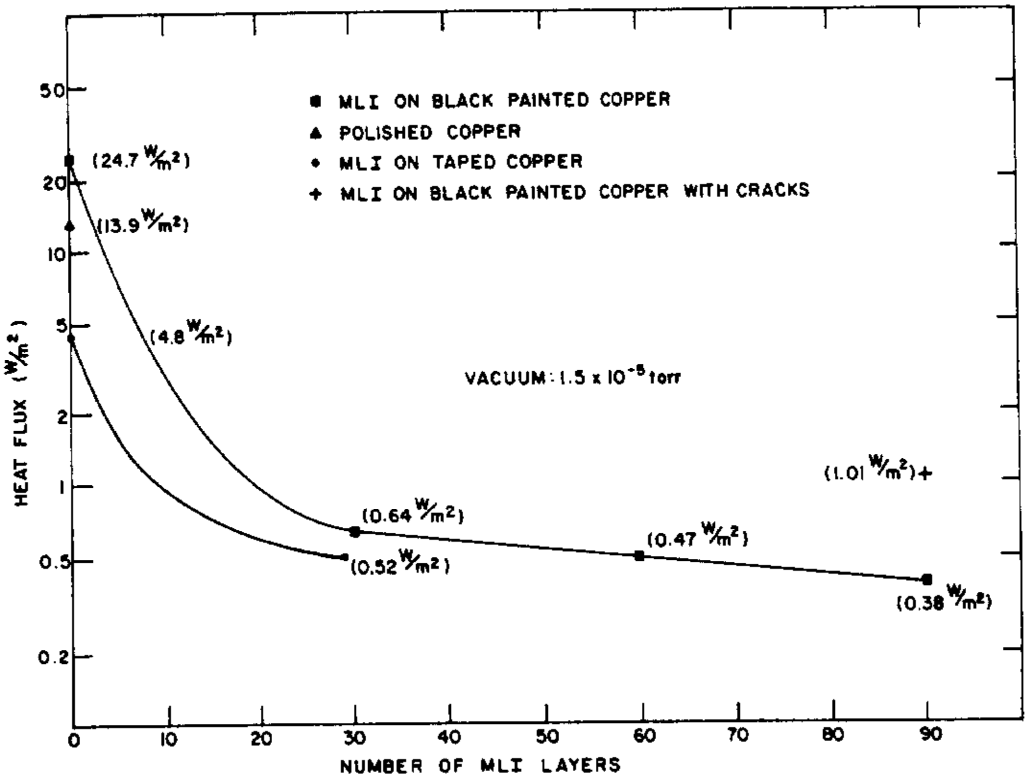

Fig. 2. Heat flux as a function of the number of MLI layers and surface preparation.

eight runs, normalized to a vacuum of 1 x 10^{-5} torr. It can be seen that the heat flux without MLI has the ratio black:polished:taped = 1:0.56:0.19. The MLI data shows that heat fluxes between 0.5 and 1.0 W/m^2 can be achieved with approximately half as many multilayers on a taped surface as on a bare one. The data indicates the marginal benefit of using more than about 30 layers of MLI.

Temperature distribution with good vacuum

Figure 3 gives the observed temperature distributions in the MLI at an overall vacuum of 1 x 10^{-5} torr for the systems studied. The temperature distribution is determined by radiation, by interlayer gas conduction which is a function of the interlayer vacuum and by solid conduction which depends on the layer to layer contact pressure[4]. These effects can be studied by considering the entire 90-layer multilayer system to be divided into three regions, the innermost 15 layers, layers 15 to 60, and layers 60 to 90. The apparent thermal conductivity $K = (Q/AD)(n/\Delta T)$ where n and ΔT are the number of layers and the temperature difference for each region. From the data for 90 layers on a black painted surface $N/\Delta T(0\rightarrow15 \text{ layers}) = 0.18$ layers/K, $N/\Delta T(15\rightarrow60 \text{ layers}) = 0.51$ layers/K and $N/\Delta T(60\rightarrow90 \text{ layers}) = 0.66$ layers/K. Since (Q/AD) is approximately constant, $K(60\rightarrow90) > K(15\rightarrow60) > K(0\rightarrow15)$ which implies that residual gas conduction and radiation are more significant in the outer section (60 to 90 layers) of the MLI blanket than in the inner (0 to 15 layers).

The second layer of the 30-layer system, the eighth of the 60-layer system and the fifteenth of the 90-layer are at 158 K. The apparent thermal conductivity for $\Delta T = (158-77)$K was calculated for each system, using Q from Fig. 2. The ratio K(30 layers) : K(60 layers) : K(90 layers) = 1:3:4 which shows the combined effect of interlayer vacuum and contact pressure as the number of layers is increased.

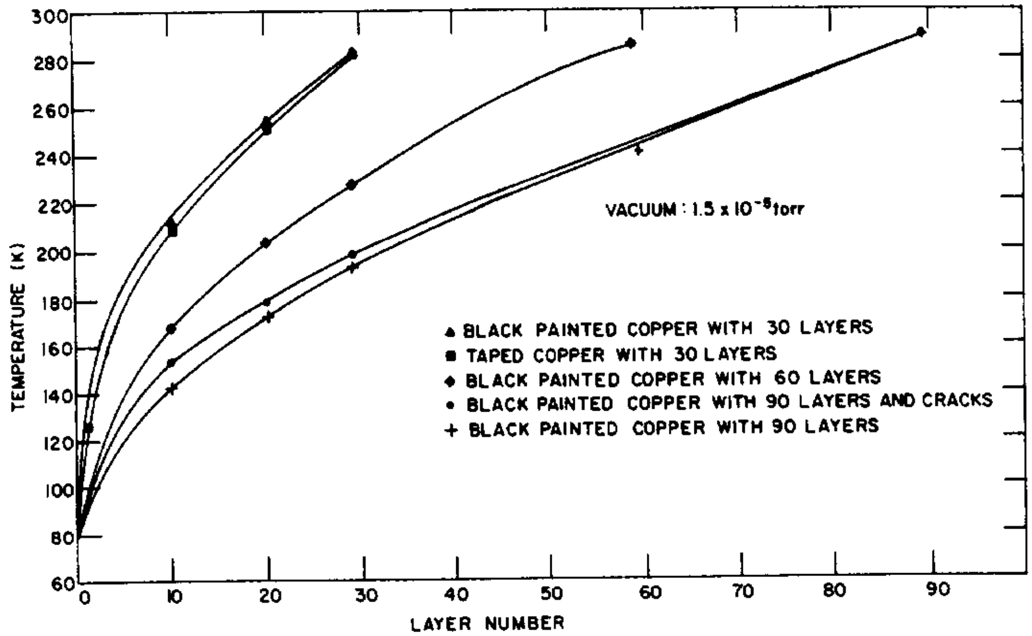

Fig. 3. Temperature distribution of MLI for various systems.

Effect of overall vacuum on heat flux and temperature distribution

Figure 4 shows the heat flux as a function of overall vacuum for the insulation systems studied. For non-MLI systems, the heat flux is determined by free molecular conduction. The different slopes are the result of the accomodation coefficient being sensitive to the surface condition. The heat flux for MLI systems is almost independent of the vacuum below 10^{-4} torr but increases rapidly with vacuum above this value. The data suggests that the performance of an MLI system might be comparable to that of a non-MLI system for a vacuum level above about 2 to 5×10^{-3} torr.

Figure 5 shows that the temperature of the intermediate layers decreases as the overall vacuum and presumably the interlayer vacuum gets worse. The temperature of the first layer was measured in the 30-layer run as 128.5 K at 1.5×10^{-5} torr, 87 K at 1.5×10^{-4} torr, and 83.4 K at 9.5×10^{-4} torr.

Effect of "black" crack

The overall thermal performance of the MLI systems used in large scale cryogenic applications is often poorer than one would expect from laboratory measurements. This performance degradation has usually been qualitatively attributed to penetrations through the MLI and to cracks between prefabricated MLI blankets. The effect of cracks was investigated by cutting twelve cracks, each 6 x 228 mm^2, in the 90-layer MLI blanket applied over a black painted copper surface. The heat load increased from 0.86 W without the cracks to 2.28 W (Fig. 2). This increase is a factor of 3.5 greater than the increase predicted from a simple calculation using the total crack area (0.0164 m^2) and the radiation heat flux measured without MLI (24.7 W/m^2, Fig. 2). From the data in Fig. 4 it can be shown that the performance of the MLI system with cracks was 20% more degraded by a vacuum loss from 1×10^{-5} to 5×10^{-4} torr than the same system without cracks.

Figure 6 shows that the temperature of an interior layer is a stronger inverse function of the vacuum for MLI systems with cracks than

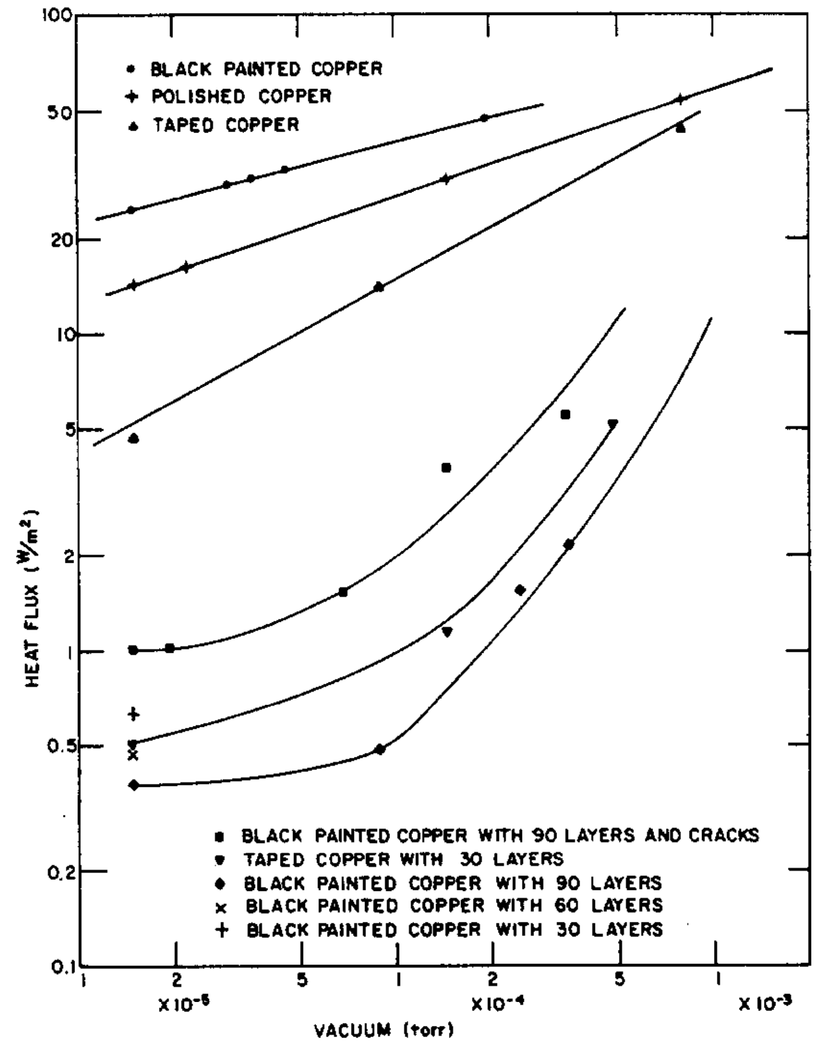

Fig. 4. Heat flux as a function of overall vacuum for systems studied.

without (Fig. 5). The difference in the temperature of the 29th layer with and without cracks is shown as a function of overall vacuum in Fig. 7. T_a is located far from the area of the crack. The temperature of a point on the 29th layer is determined by its proximity to the crack as shown in Fig. 8 as a function of overall vacuum. The temperature is higher near the crack than remote from it. Figure 9 shows the cracks.

CONCLUSION

The data shows the use of aluminum tape to be advantageous in the 300 to 77-K temperature region. In cases where there is inadequate space for MLI or for geometries on which it is difficult to apply MLI, the use of tape alone might be satisfactory. If tape is used with MLI the number of MLI layers can be reduced, which should improve the pump-down characteristics of the insulating vacuum system.

Cracks in MLI layers or blankets should be avoided since the data implies that the effect on the heat flux is more serious than can be easily calculated. We postulate that cracks in a tape-MLI system will cause less degeneration of the thermal performance and plan to investigate this immediately.

Knowledge of the temperature distribution through the MLI proved very helpful in analyzing and understanding the effects of vacuum level, contact pressure, etc, on the heat flux.

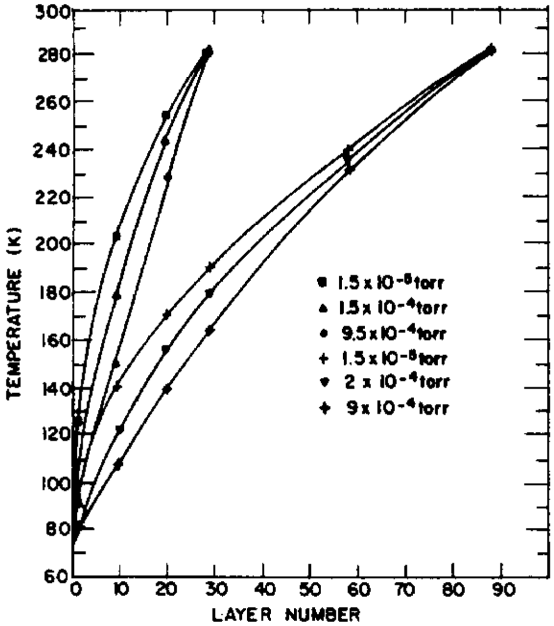

Fig. 5. Temperature distribution as a function of overall vacuum for 30 and 90 MLI layers on a black painted inner plate.

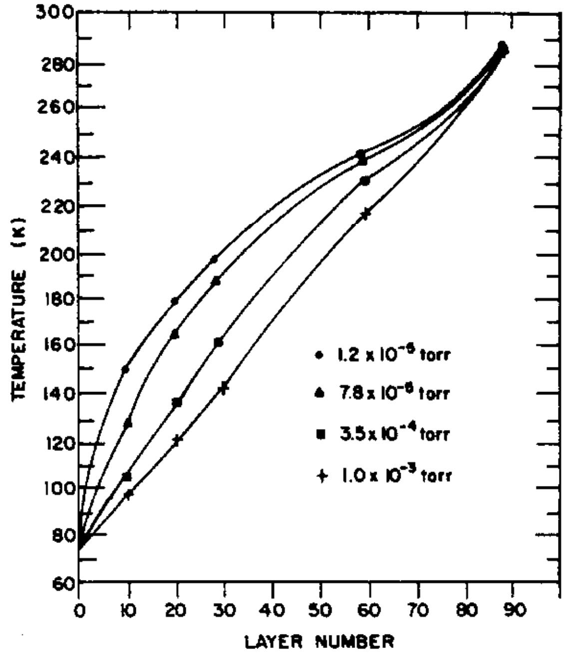

Fig. 6. Temperature distribution as a function of overall vacuum for 90 MLI layers with cracks.

NOMENCLATURE

A	Total area of inner plate
$\bar{A}$	Average layer to layer contact area
C	Residual gas conductivity factor
D	MLI layer density
E_o	Emissivity factor between boundary and adjacent area
E_s	Emissivity factor between any two adjacent layers
k	Average solid thermal conductivity
K	Average apparent thermal conductivity
N	Total number of MLI layers
n	Total number of MLI layers in region
P	Absolute pressure in MLI system
Q	Total heat transfer rate
T_h	Temperature of warmer surface
T_c	Temperature of colder surface
α	Accomodation coefficient for residual gas conduction
δ	Thickness of Mylar on MLI
ΔT	Temperature difference across an MLI region
σ	Stefan-Boltzmann constant

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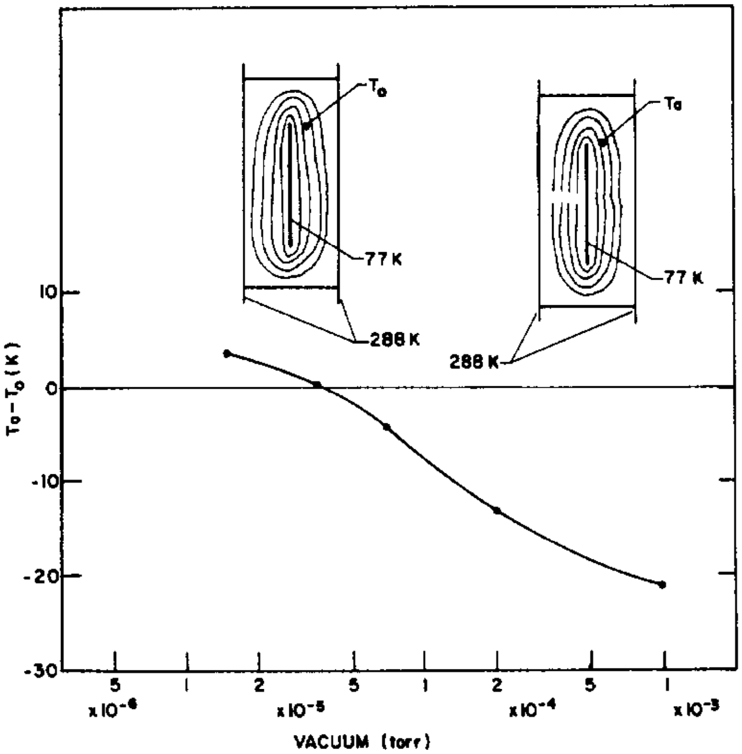

Fig. 7. Difference in the temperature of the 29th layer with and without cracks in the 90-layer MLI system as a function of overall vacuum.

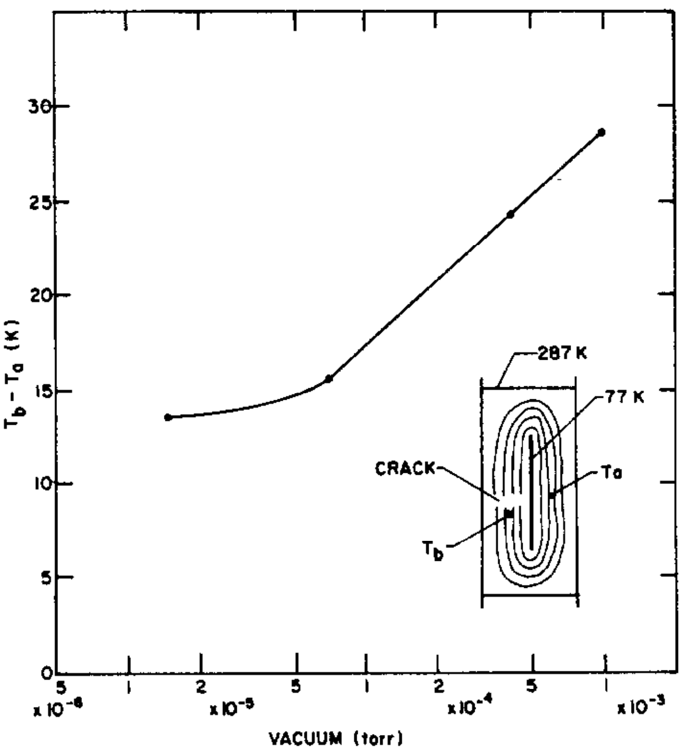

Fig. 8. Difference in temperature of points on the 29th layer with cracks as a function of overall vacuum.

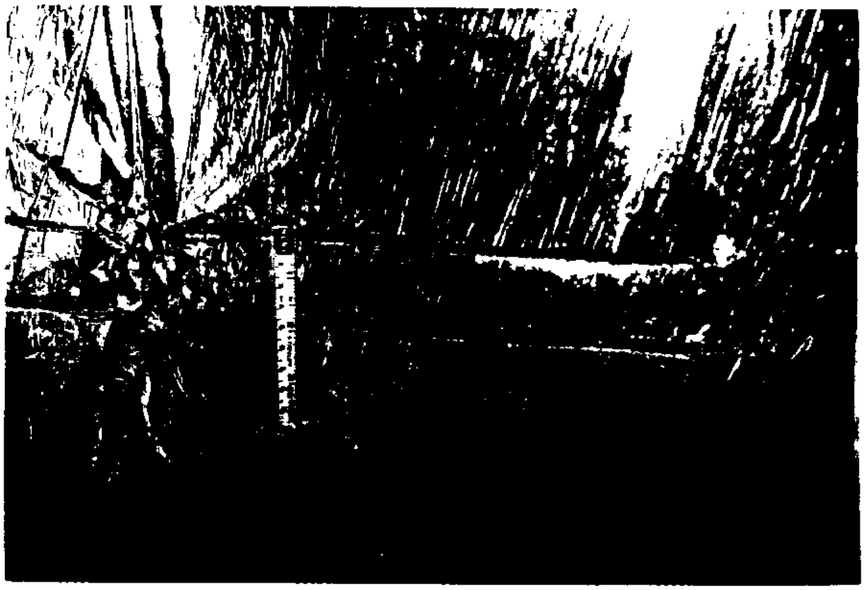

Fig. 9. Cracks in 90-layer MLI blanket.

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